Computer-based Clinical Instrumentation for Processing and Analysis of Electroneuromyographic Signals in the Upper Limb

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Abstract: **A computer-based clinical instrument was developed to simultaneously acquire, process, display, quantify and correlate electroneuromyographic (ENMG) activity in the upper limb in humans. This system was designed around AMLAB^{Ò} analog modules and software objects called ICAMs. The system consists of a nerve stimulator block, a time domain EMG block with evoked response averaging capability, a counter block and a data storage and retrieval block. The system acquires and displays the raw electromyographic (EMG) signal in the Flexor Carpi Radialis (FCR) muscle and quantifies its root-mean-squared (RMS) value. It also acquires the elicited H-reflex and M-response and displays them along with raw EMG signals in one integrated environment. This system has been designed to study the H-reflex and M-response in the upper limb of normal subjects and Carpal Tunnel Syndrome (CTS) patients. It could be easily modified to acquire, process and analyze the ENMG signals in other parts of the human body to assess the continuity and function of the sensory and motor pathways.**

In this paper, we present an integrated system to simultaneously measure and analyze the electroneuro-myographic activities in the upper limb.

Keywords: Electroneuromyographic (ENMG) signals; Computer-based clinical instrumentation; Biomedical signal processing and analysis; H-reflex; M-response; AMLAB$^®$; Carpal Tunnel Syndrome, FCR muscle.

I. INTRODUCTION

Electromyographic examinations usually record the electrical activity of voluntary muscles at rest or during volitional activity. Additionally, electrical stimulation is required in electroneurographic studies for measurement of nerve conduction velocity and response latency. H- and M-waves are evoked potentials elicited by electrical stimulation of spinal nerves to assess the continuity and function of the sensory and motor pathways. In addition, they provide objective methods to study the central part of the reflex arc.

Traditionally, the measurement of the H-reflex and M-response is performed with the same equipment used in conventional motor and sensory nerve conduction testing. It comprises of a nerve stimulator with isolated output, a set of stimulating and recording electrodes applied to the subject, differential amplification of the evoked signals, bandpass filtering, sweep trigger and timing facilities and CRT display as well as paper or tape recording.

With development of high-performance microprocessors and their deployment into contemporary electrodiagnostic instruments, a fundamental shift in design from traditional analog circuit technology to high-speed digital technology (with extensive signal processing capabilities) has occurred. The most tangible benefit of the use of microprocessors and digital signal processing techniques in electrodiagnostic instrumentation has been the improved ease, accuracy, and quality of routine nerve conduction velocity measurements and evoked response studies. Current digital ENMG instruments consist of an analog subsystem that performs nerve stimulation, signal amplification and filtering. More importantly they have a microcomputer together with its associated components (i.e., memory, keyboard, non-volatile storage, etc.), a high-resolution video display system and an analog-to-digital converter.

In digital ENMG equipment, the microcomputer coordinates the activities of various components of the instrument. For example, it changes the gain of the amplifiers, modifies the corner frequencies of the filters and synchronizes the nerve stimulation and waveform acquisition during nerve conduction and evoked potential studies. In addition, by using mathematical algorithms it performs a wide variety of signal processing tasks to enhance the quality of the signals (such as noise removal) or to extraction of quantitative features from them.

During elicitation of H-reflex in the FCR muscle, usually two problems are encountered. First, a special facilitation technique is required to consistently obtain the H-reflex in the FCR muscle. The H-reflex is only obtainable without facilitation in the gastrocnemius-soleus muscle of the lower limb. Even though, the H-reflex can also be obtained in the FCR muscle in the upper limb, a facilitation technique may often be required to elicit this response. H-reflex in the FCR muscle has been obtained without facilitation in 70% of normal subjects. But by using a facilitation technique, the H-reflex has also been obtained in the remaining 30% [1]. A mild voluntary contraction of the FCR muscle can be used as a facilitation technique for elicitation of H-reflex. To keep this background contraction throughout the test at an acceptable standard level within subject or between different subjects, feedback of raw and root mean squared (RMS) values of background EMG to the subject is crucial. However, this facility is not a standard feature of most commercially available ENMG instruments.

The second problem encountered is the small magnitude of the elicited H-waves, which are recorded in the presence of random noise and above background voluntary contraction. In this situation, the background EMG activity as well as the system noise, obscures the response. Evoked response

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25 Oct 2001	N/A	-

Title and Subtitle	Contract Number
Computer-Based Clinical Instrumentation for Processing and Analysis of Electroneuromyographic Signals in the Upper Limb	Grant Number
	Program Element Number

Author(s)	Project Number
	Task Number
	Work Unit Number

Performing Organization Name(s) and Address(es)	Performing Organization Report Number
School of Informatics and Engineering, Flinders University of South Australia	

Sponsoring/Monitoring Agency Name(s) and Address(es)	Sponsor/Monitor's Acronym(s)
US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes
Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Oct 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom

Abstract

Subject Terms

Report Classification	Classification of this page
unclassified	unclassified

Classification of Abstract	Limitation of Abstract
unclassified	UU

Number of Pages
4

averaging is a powerful method regularly used to remove noise and background activity to improve the quality of the response. However, the averaging capability is not a standard feature in most of ENMG instruments.

The capabilities required to address the above-mentioned limitations are not standard features of conventional and most commercially available ENMG instruments. Since such instruments, if commercially available are expensive, a computer-based system was developed to study the ENMG signals in the upper limb in a comprehensive and integrated manner.

II. INSTRUMENTATION

A. System hardware
AMLAB Analog Modules and Workstation: The integrated ENMG system was designed and implemented around AMLAB (AMLAB International, Sydney, Australia) analog modules and software objects called ICAMs [2].
AMLAB electrical stimulator: In electroneuromyography, a popular method to stimulate the nerves and evoke the muscular responses is by using rectangular electrical pulses. A constant current bipolar AMLAB stimulator (AMLAB Accessory Stimulator) was used to provide rectangular pulses with a duty cycle of 0.8 msec and a frequency of 0.5 Hz. The stimulator could provide current pulses with an amplitude range of 0 to 100 mA (0 to 500 V).

B. System software
The input signals required for development of the integrated ENMG system comprised of surface EMG signals due to voluntary contractions as well as the electrically evoked H-reflex and M-response from the FCR muscle.

The raw EMG signals were first filtered using a second-order Butterworth bandpass filter (10-500 Hz). The filtered EMG signals were then amplified (G=1000) by an electrically isolated low-noise biopotential amplifier with high input impedance (500 MΩ) and high common mode rejection ratio (CMRR = 120 dB). The amplified signals were then band-limited by using an anti-aliasing filter with a cut-off frequency of 500 Hz before sampling. For adequate presentation of surface EMG signals and the H- and M-responses derived from them, we chose a sampling rate of 1000 Hz. Four functional blocks were required for implementation of the integrated ENMG system. These functional blocks comprised a block to generate electrical pulses and run the AMLAB electrical stimulator; a block to display the time-domain EMG signals as well as the M- and H- responses; a block to count various stages of the experiment and to generate all traces simultaneously; and a block to store the data stream to disk for future retrieval.

The ENMG system required four sets of display windows: 1) A window to display the raw EMG signal. 2) A window for the digital display of the RMS values of the EMG signal. 3) A set of four windows for the display of averaged evoked responses with different sensitivities to monitor the H- and the M-waves. 4) A set of displays consisted of a menu window to choose stimulus train number, a window to show the running number of the stimulus, a window to show the stimulus start/stop check box, and finally a window to display the execution page control of the stimulus intensity. Figure 1 shows a flowchart illustrating the steps involved in building the schematics for each functional block and their integration into an instrument.

C. System implementation
Electrical stimulator block: This block provided rectangular pulses with adjustable duty cycle, frequency and amplitude. The stimulator block consisted of: 1) a Square Wave VCO ICAM to implement a square wave generator, 2) a Pulse Generator ICAM to generate a single pulse when triggered, 3) a Counter ICAM to count trigger events, 4) a Variable Set Point ICAM to provide a run time switch for control of stimulus amplitude. 5) a Radio Button ICAM to allow the user to interactively control the instrument while it was running, 6) a Numeric Display ICAM to display the numeric value of the stimulus number when triggered and 7) an Analog Output ICAM to represent a hardware output buffer from the Digital-to-analog Converter (DAC). The last-mentioned ICAM was used to supply an analog output signal to the stimulator.
The EMG & evoked response block: This block recorded and displayed the time-domain EMG signals and the H- and M-responses derived from these signals by evoked response averaging. The EMG block consisted of a biopotential amplifier and an anti-aliasing filter, a set of mathematical functions for rectification and smoothing of the raw EMG data and evoked response averaging and finally, a block for displaying the EMG data and the evoked responses.
The data storage block: This block simultaneously recorded and stored ENMG data as "archive" files. Data collected could be reviewed later by running the files "off-line". A Disk Destination ICAM was used to store data streams to the hard disk for future retrieval.

D. System repeatability & calibration
An important step in establishing the efficacy of any new instrument is to investigate its repeatability, which is defined as the extent to which identical stimuli can produce identical responses. Usually a test-retest protocol is used to assess the ability of the instrument to reproduce the test results under various operating conditions. Data cannot be interpreted with confidence unless the instruments used to collect, record, and process the data possess high degree or repeatability.
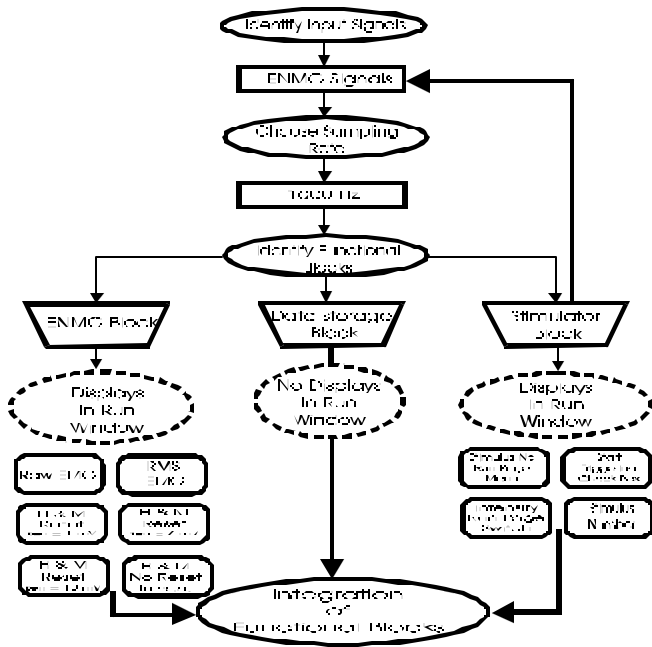
Figure 1. Flowchart of the functional block diagram of the integrated computer-based ENMG system.

Recently, features such as H- and M-waves latencies, H-reflex amplitude, H_{max}/M_{max}, etc. have been used as easily obtainable measures of motoneuron pool excitability [3,4]. Such measures may also provide valuable information to monitor the neuropathology of cervical spinal root compression and segmental reflex behavior. Therefore to be able to effectively utilize the quantitative features of the H-reflex and M-response characteristics in clinical diagnostic tests, it was crucial to establish the between-days repeatability of the measurements made by the newly developed system.

To achieve this task, fourteen asymptomatic subjects with no history of neurological or upper quarter musculoskeletal injury were tested on two occasions at least 72 hours apart at approximately the same time of the day. These subjects included 8 males and 6 females in the age range 22-65 years (mean 32.8; SD $\pm$ 11.2). The mean height of subjects was 168.3 ($\pm$ 10.4) cm and the mean weight was 62.7 ($\pm$14.3) kg. Statistical analyses were performed on latencies and peak-peak amplitudes of the H-reflex and M-response of the FCR muscle as well as the H_{max}/M_{max} to assess between-test repeatability of measurements. Two different statistical measures were used to report these between-test reliabilities: paired t-tests were used to detect systematic bias between measured values in day one and two. However, since these tests give information about systematic differences between the means of two sets of data, the Intra-Class Correlation (ICC) was also included. It is current practice to accept ICC values in the range 80-100% as "excellent reliability" and ICC values in the range 60-80% as "good reliability", whereas values below 60% indicate "poor reliability".

Calibration of the overall system was also necessary to make sure the measurements are accurate. We used a calibration method and procedure as described elsewhere [2].

III. EXPERIMENTAL METHODS

A. Electrical stimulation technique

A surface stimulating technique was used for stimulation of median nerve at the cubital fossa. The electrical stimulator block controlled the stimulator to provide isolated output current stimuli. The stimulating electrodes were 2 saline-soaked felt pads mounted inside a plastic mold with 2.5 cm between anode and cathode. These electrodes were positioned with the cathode proximal to the anode and in line with the median nerve in the cubital fossa just medial to the tendon of biceps brachii. The selectivity of the stimulation was carefully ascertained by observing and palpating the contraction of the FCR muscle.

The electrodes were fixed with a rubber strap to maintain pressure on them throughout the experiment. Stimulation parameters were 0.8 ms rectangular pulses at a frequency of 0.5 Hz. Stimulus durations of 0.5-1 ms were more selective for recruitment of the afferent fibres and stimulus frequencies of less than 1 Hz prevented the effects of low frequency depression. In all cases, the stimulus started at 0.5 mA and was increased at 0.3 mA increments until a maximal response was achieved. To ensure that the applied stimulus was maximal, two horizontal cursors were placed on positive and negative peaks of the evoked response and if further increase in the stimulus intensity caused no increase in the amplitude of the evoked response, the applied stimulus amplitude was considered maximal.

B. Elicitation and recording of H-reflex and M-response

H-reflex and M-responses were obtained with self-adhesive pre-gelled electrodes [2]. The pairs of electrodes were positioned with an inter-electrode distance of 2 cm over the FCR muscle at one-third of the distance from the medial epicondyle to the radial styloid. To identify the belly of the FCR muscle, the subject was asked to flex the wrist-thumb component with the thumb and little finger in opposition, and the investigator provided mild resistance to the flexed wrist at the thenar muscle. During this maneuver the FCR muscle contracted and bulged in the proximal part of forearm. The reference (ground) electrode was a lip-clip electrode, which was clipped onto the subject's lip to make close contact with the mucosa, which has a very low electrical resistance [5].

IV. RESULTS

Figure 2 shows a typical and representative H-reflex and M-response acquired from the FCR muscle in a subject. The described methods and the ENMG instrument enabled us to elicit the H-reflex and M-response in the FCR muscle during an isometric contraction. The visual feedback from recorded waveforms in the ENMG system allowed us to standardize the background EMG activity in different subjects. The

averaging of the evoked responses successfully removed the noise and background activity due to voluntary contraction of the FCR muscle and improved the signal-to-noise ratio (SNR) of the evoked H-reflex and M- response. Figure 3 shows the front panel of the developed ENMG system.

Statistical analysis performed on the mean values of H- and M-wave latencies and amplitudes as well as H_{max}/M_{max} revealed that there was excellent reliability for H-reflex and M-response latencies and M-response amplitude (ICC = 0.8, 0.89, 0.86, respectively). There was a good reliability for H-reflex amplitude and H_{max}/M_{max} (ICC = 0.68 & 0.64, respectively). The paired t-test revealed that the mean difference between all of the above-mentioned values for session one and two were not statistically significant (n = 14, α = 0.05).

V. DISCUSSION

Using the developed ENMG system, we were able to record the H-reflex from all subjects during isometric contraction of the FCR muscle. The FCR muscle H-reflex showed characteristics similar to those of a classic soleus H-reflex. Reflexes recorded showed an increase to maximum peak-to-peak amplitude with increasing stimulus intensity. Further increase in stimulation intensity showed a decrease in reflex amplitude until it was completely blocked, which is a well-known behavior of the H-reflex recruitment with stimulus strength. This decrease was probably due to blockage of conduction in some large-diameter nerve axons resulting in a decreased recruitment of the motoneuron in eliciting a large reflex amplitude. The H-reflex was bi- or tri-phasic in most of the subjects. It was also observed that the H-reflex shape was similar to the M-response shape, implying that records were sampling excitability of motoneuron (H-reflex) and muscle fibres (M-response) of the same population. The latency difference between the M-response and the H-reflex showed an average value of 14.83 msec. This value agrees with the time it takes the electric stimulus to travel from the stimulation site to the spinal segment and back to the stimulation site. This time corresponds to an average conduction velocity of 70 m/sec throughout the FCR reflex arc.
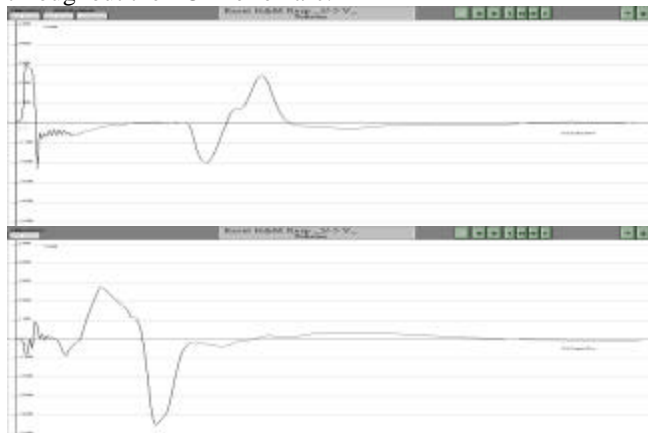

Figure 2. Typical H-reflex (top) and M-response (bottom) from the FCR muscle of a subject.

Figure 3. User interface of the developed ENMG system.

The findings in the this study support the idea that the H-reflex and M-response in the FCR muscle have a fairly constant latency and amplitude during a prolonged isometric contraction and the H_{max}/M_{max} would not significantly (α=0.05) change in a given person on repeated testing on different days and hence could be used as an invariant and reliable measure of ENMG activity. It is important to mention that the observed variability is a combined result of subject response variability (which constitutes the bulk of the variability) and to a much smaller extend the equipment variability including electrode positioning, skin preparation, etc.

VI. CONCLUSIONS

In this paper, we described a computer-based ENMG system suitable for quantitative study of H-reflex and M-response in the human upper limb. We used this system to elicit and study the H-reflex and M-response in fourteen healthy subjects. H-reflex and M-response latencies and M-response amplitude were found to show excellent repeatability; H-reflex amplitude and H_{max}/M_{max} demonstrated good repeatability. The high degree of repeatability for H-reflex and M-response characteristics imply that the instrument and protocol used are highly reliable, hence they can be used for valid clinical measurement of these characteristics in normal subjects. In future studies, the system can be used to study patients with signs and symptoms of CTS.

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